Future Large Single Aperture Ground Based Submillimeter Telescopes

G.J. Stacey, Cornell University

The Present

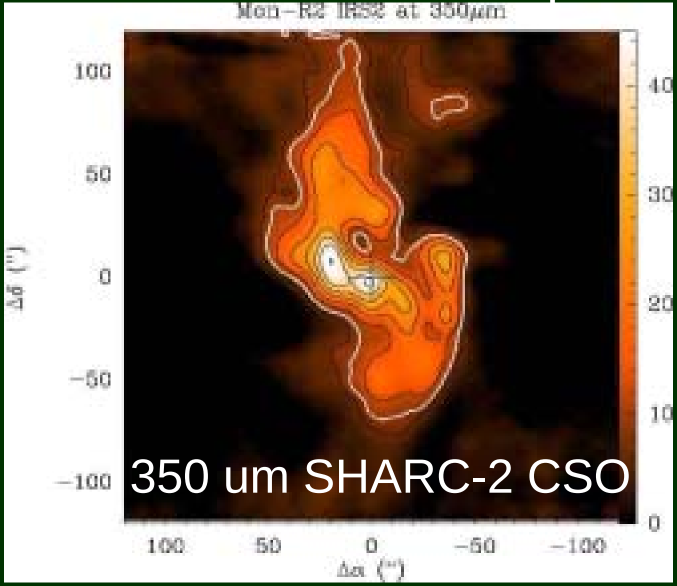
At present, we have a few 10 to 15 m class telescopes of very good surface quality (15 to 25 um rms) in very good submillimeter sites

- 10.4 m CSO: Mauna Kea
- 15 m JCMT: Mauna Kea
- 10 m HHT: Mount Graham

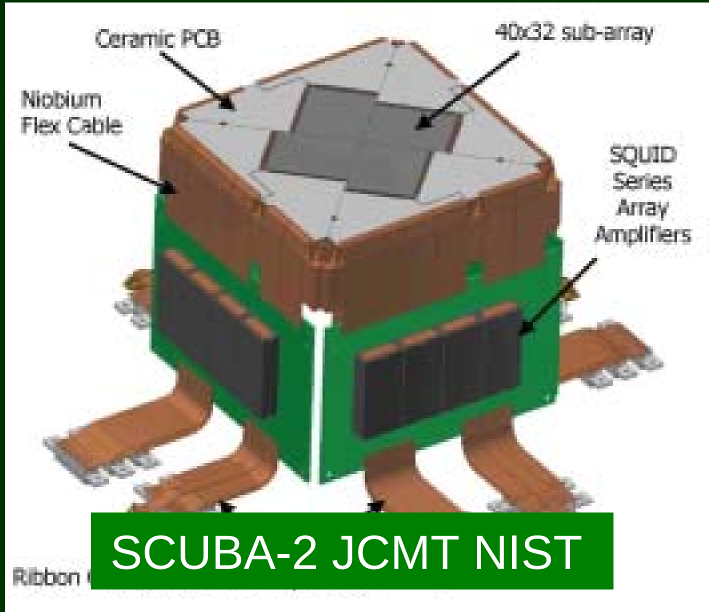
The Present

- These telescopes have delivered high sensitivity and ground breaking science with modest arrays
  - CSO: SHARC – 40 pixels
  - JCMT: SCUBA – 128 pixels
- New large format arrays promise exciting new science
  - SHARC II – 384 pixels
  - SCUBA II – 5000 pixels

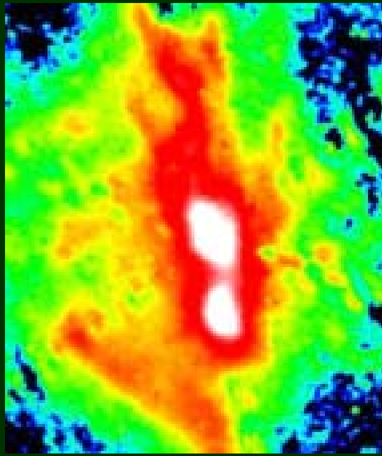

SHARC-2 CSO GSFC



350 um SHARC-2 CSO



SCUBA-2 JCMT NIST

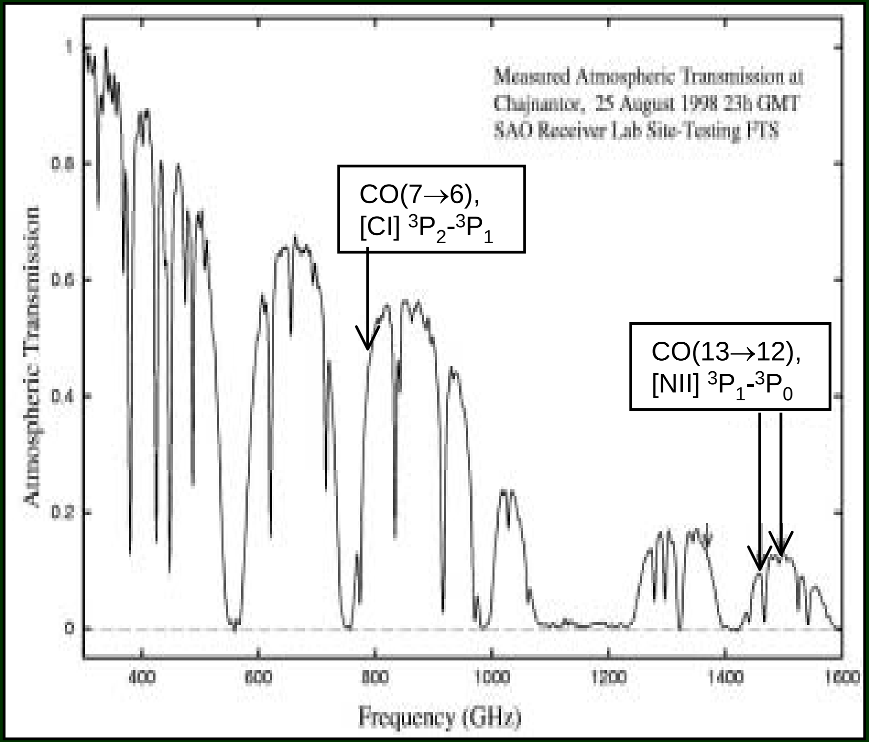

SCUBA-2 JCMT Johnstone & Bally

The Near Future

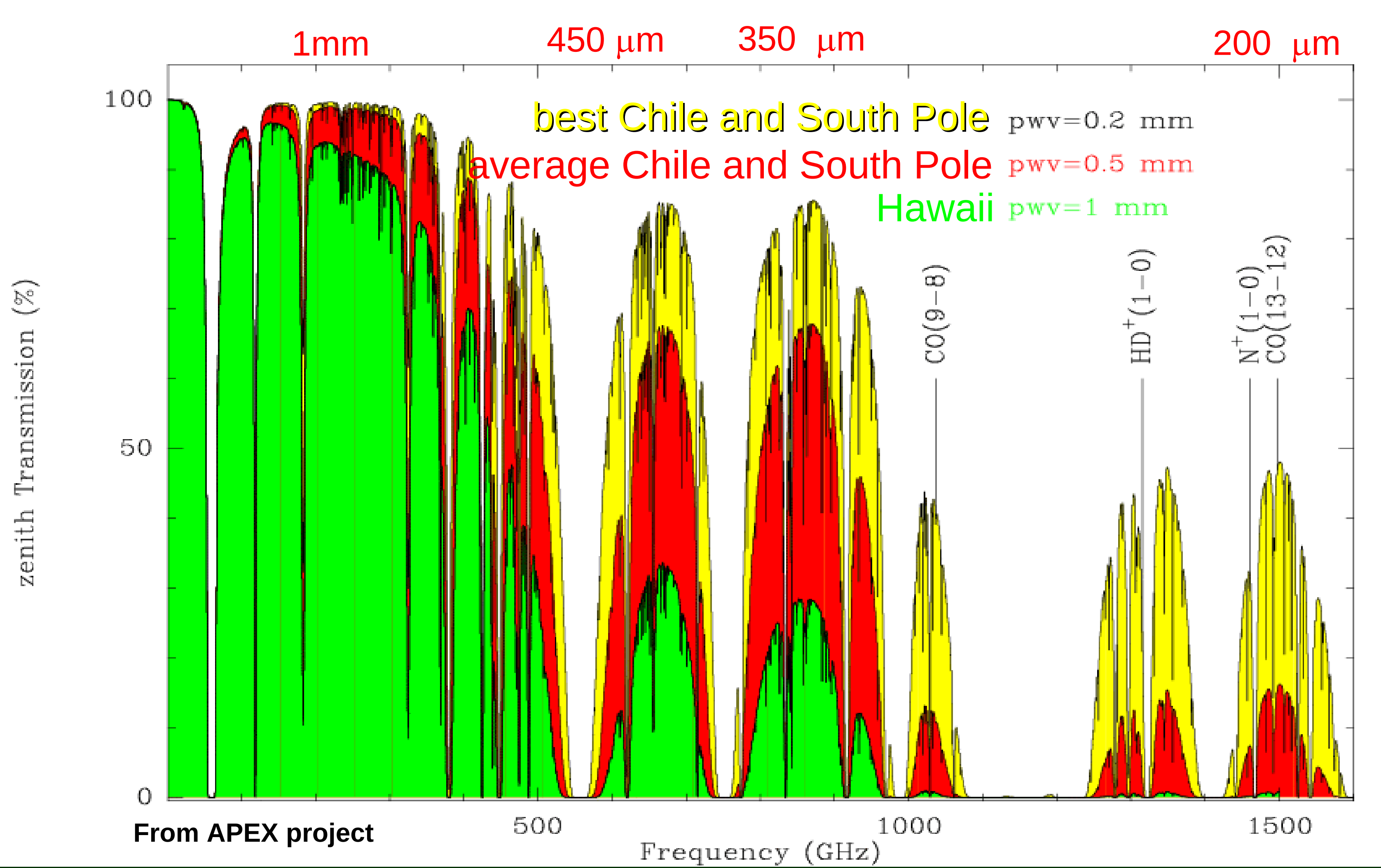
- In the near future we expect several new facilities to spring up in excellent submillimeter sites
  - Movement towards short submillimeter $\Rightarrow$ avoids confusion
  - Movement towards better sites
- I will talk about 4 of these in order of their first light:
  - ASTE: 10 m
  - APEX: 12 m
  - South Pole Telescope: 10 m
  - Atacama Telescope: 25 m
- Issues:
  - The Telescope
  - The Site
  - The Science

Why Ground Based?

- Largest Apertures available
  - Highest angular resolution – excepting interferometers
  - Continuum comes through in submm bands
  - Some of the most important cooling lines also are transmitted through the atmosphere
- Allows rapid implementation of latest technologies
- Large aperture single dish telescopes serve as finder telescopes for ALMA



The Sites: A Water Vapor Issue

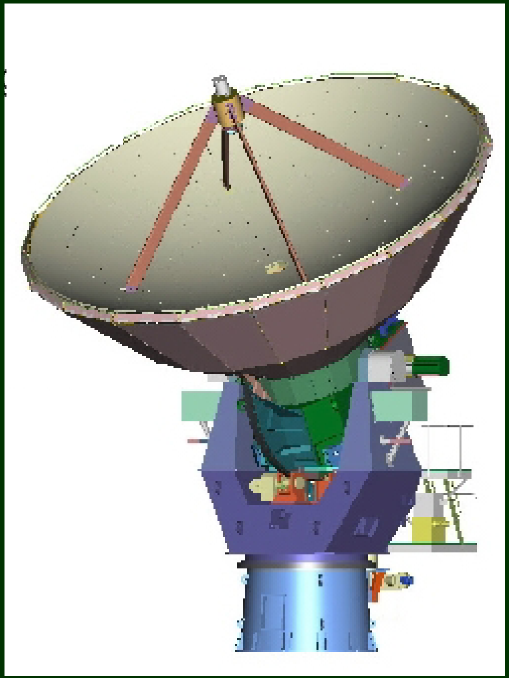


From APEX project

It is clear that Chilean and Antarctic Sites are very exciting

Atacama Submillimeter Telescope Experiment (ASTE)

- Joint project between Japan and Chile to install a high precision 10 m telescope at a high site
  - Developed for on-site evaluation of ALMA telescope technology
  - Sensitive submm observations of the southern sky
  - Surface accuracy better than 25 um, with better than 20 um rms goal
- Installed at Pampa la Bola near the ALMA site elevation 4800 m
- First testing in April 2002



(Kohno et al. 2004)

ASTE

- Receivers
  - Evaluation receivers at 100, 230 and 350 GHz
  - “Cartridge-type receivers” at 100, 500, and 800 GHz
    - Very good noise temperatures achieved
    - Maps of the LMC in [CI] (^{3}P1-$^3P_0$) line (610 um)
    - Maps of Orion in CO(7-6) line (372 um)
  - 3 color (350, 450, and 850 um) single pixel bolometer system has been used
  - Multi-pixel SIS photon detector camera in development

Project APEX

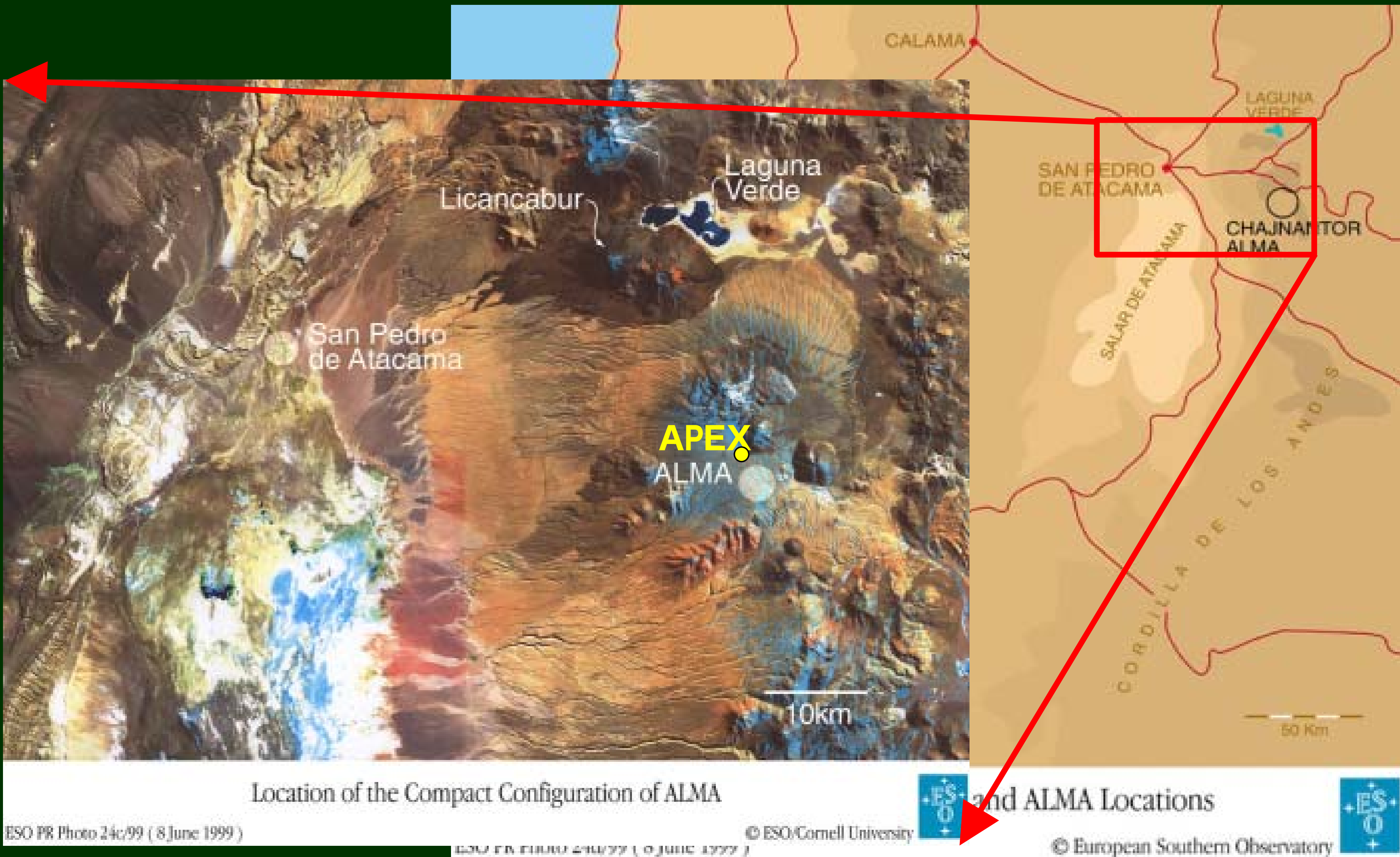
(Atacama Pathfinder EXperiment):

- Submillimeter Telescope at Llano de Chajnantor in Chile (5000 m)
- Antenna modified copy of US ALMA prototype:
  - 12 m antenna
  - Surface accuracy better than 20 um rms
- Responsibility for construction by Max-Planck-Institut für Radioastronomie, Bonn (Infrastructure help from ESO)
  - Principal Investigator: Karl Menten
  - Project Manager: Rolf Güsten
  - Project Scientist: Peter Schilke
- Partners:
  - MPIfR: 50 %
  - European Southern Observatory (ESO): 27%
  - Onsala Space Observatory, Sweden (OSO) : 23%

APEX Instrumentation

- Bolometers
  - LABOCA: 300 Element array at 870 μm (MPIfR)
  - 37 Element 350 μm (MPIfR)
  - 300 Element 2mm SZ instrument (PI Berkeley)
- Heterodyne
  - Facility single or dual pixel receivers from 210 to 500 GHz, and a THz channel (Onsala)
  - CHAMP+: 7 pixel 650 GHz/7 pixel 850 GHz (PI MPIfR)
  - THz receivers (PI KOSMA and CfA)

The APEX Site



APEX

Surface setting after holography

APEX

Nasmyth cabins and instrument containers

Status:

- Telescope Commissioning – Spring 2004
  - Optical pointing ✔
  - Holography ✔ (partly)
  - Radio Pointing ✔
- First submm observations – summer 2004
- Operation readiness – fall 2004

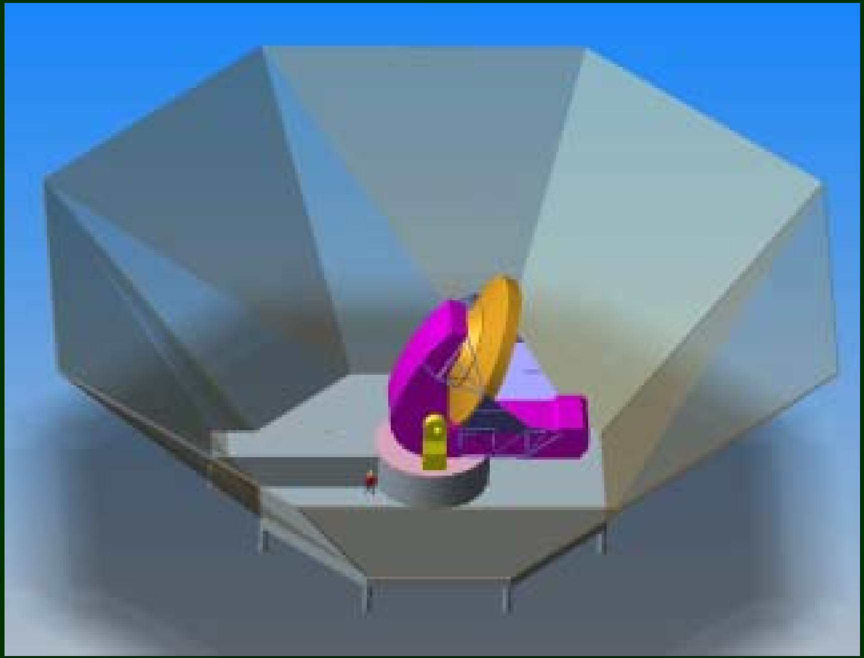
The South Pole Telescope

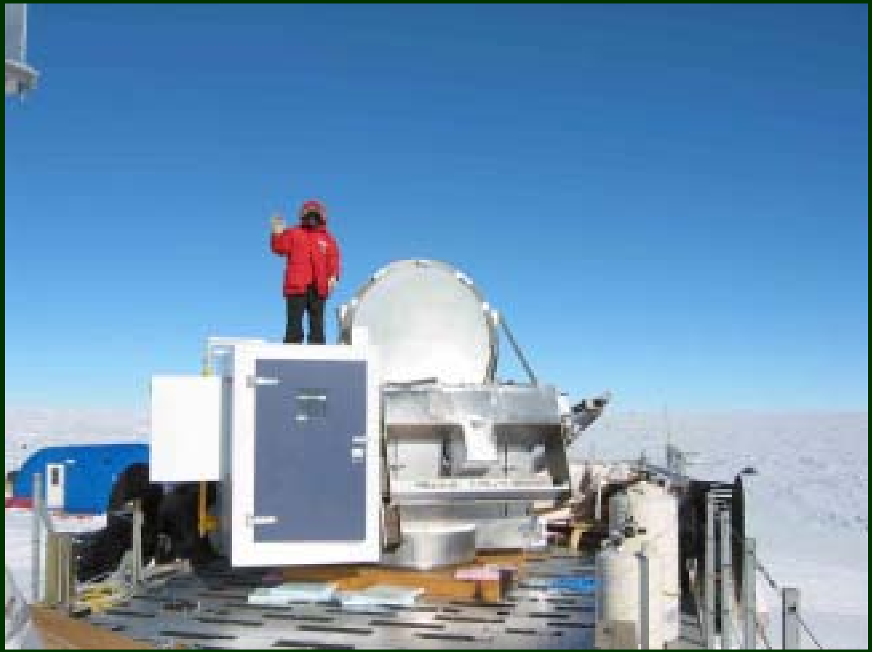
- 10 m telescope to be used at the South Pole
  - 20 um surface accuracy
  - Designed to have a large field of view
  - Off-axis design and ground shields minimizes side lobe contamination $\Rightarrow$ low noise and systematics
  - Telescope made by Vertex RSI
- Primary science: Cosmological studies of the CMBR
  - Low opacity and high stability of South Pole Site
  - Low systematics
  - Site permits continuous observations of sources that are above the horizon
- PI: John Carlstrom University of Chicago

The South Pole Telescope

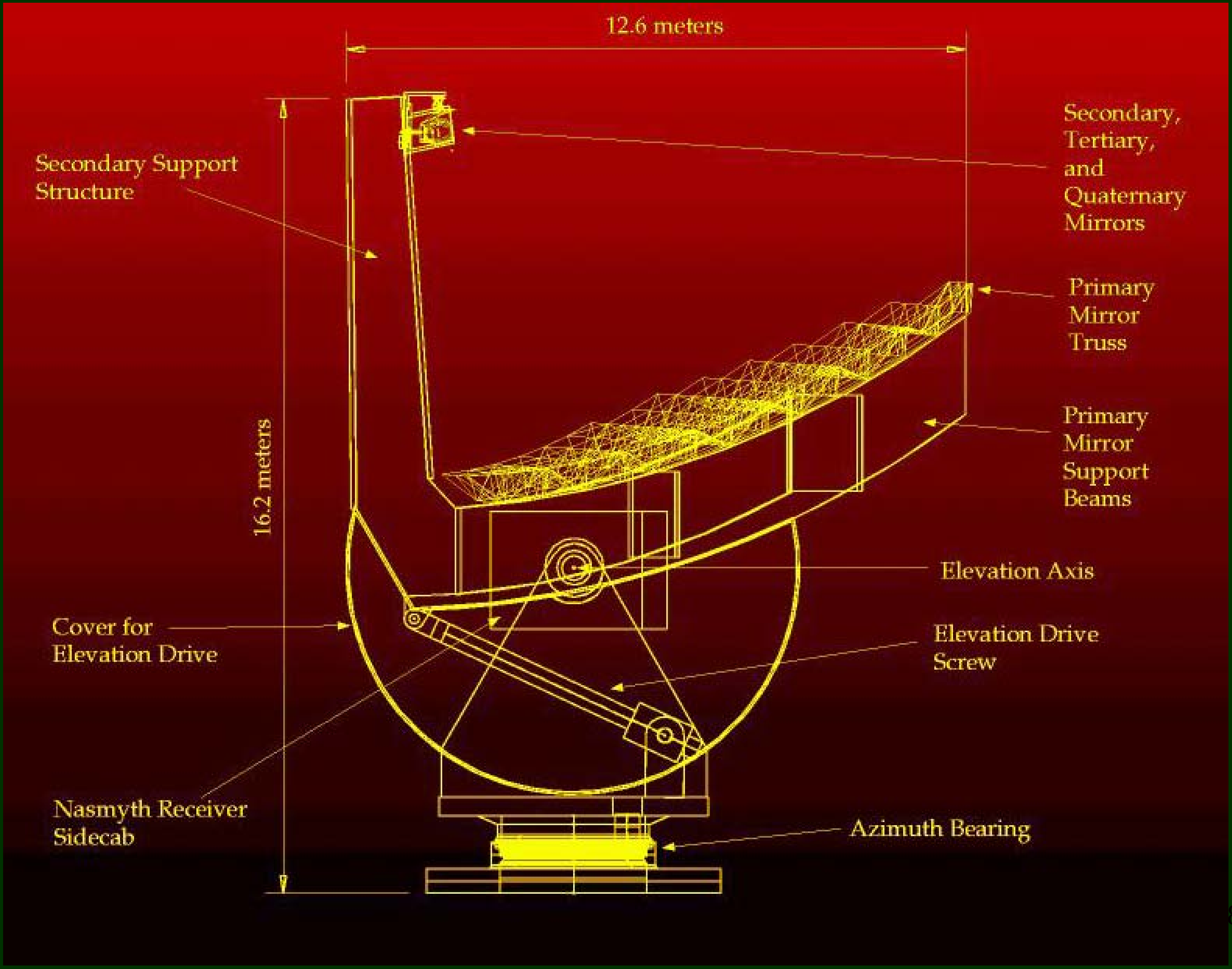
- Primary science temperature and polarization studies of the CMBR
- First observations planned for Austral winter of 2007
- Primary science should be completed after 2 to 3 years, permitting new science includes
  - Dusty Protogalaxies
  - Galactic astronomy
- Note:
  - Beam at 350 um well matched with SPITZER (30 um), SOFIA (90 um)
  - SPT surveys can provide an ALMA catalogue

SPT with Ground Shields

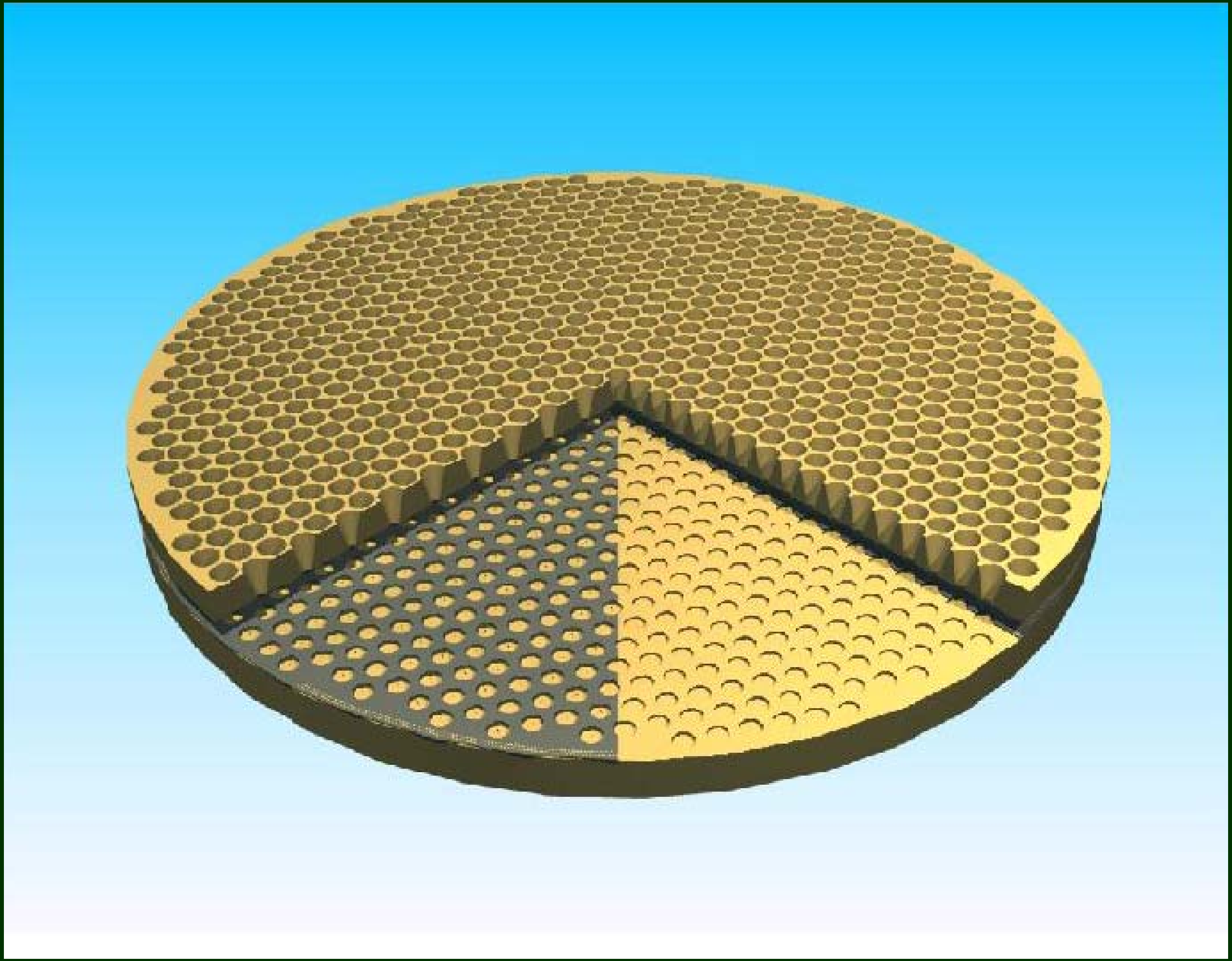




SPT Details


12.6 meters
Secondary Support Structure
Secondary, Tertiary, and Quaternary Mirrors
Primary Mirror Truss
Primary Mirror Support Beams
16.2 meters
Elevation Axis
Cover for Elevation Drive
Elevation Drive Screw
Nasmyth Receiver Sidecab
Azimuth Bearing

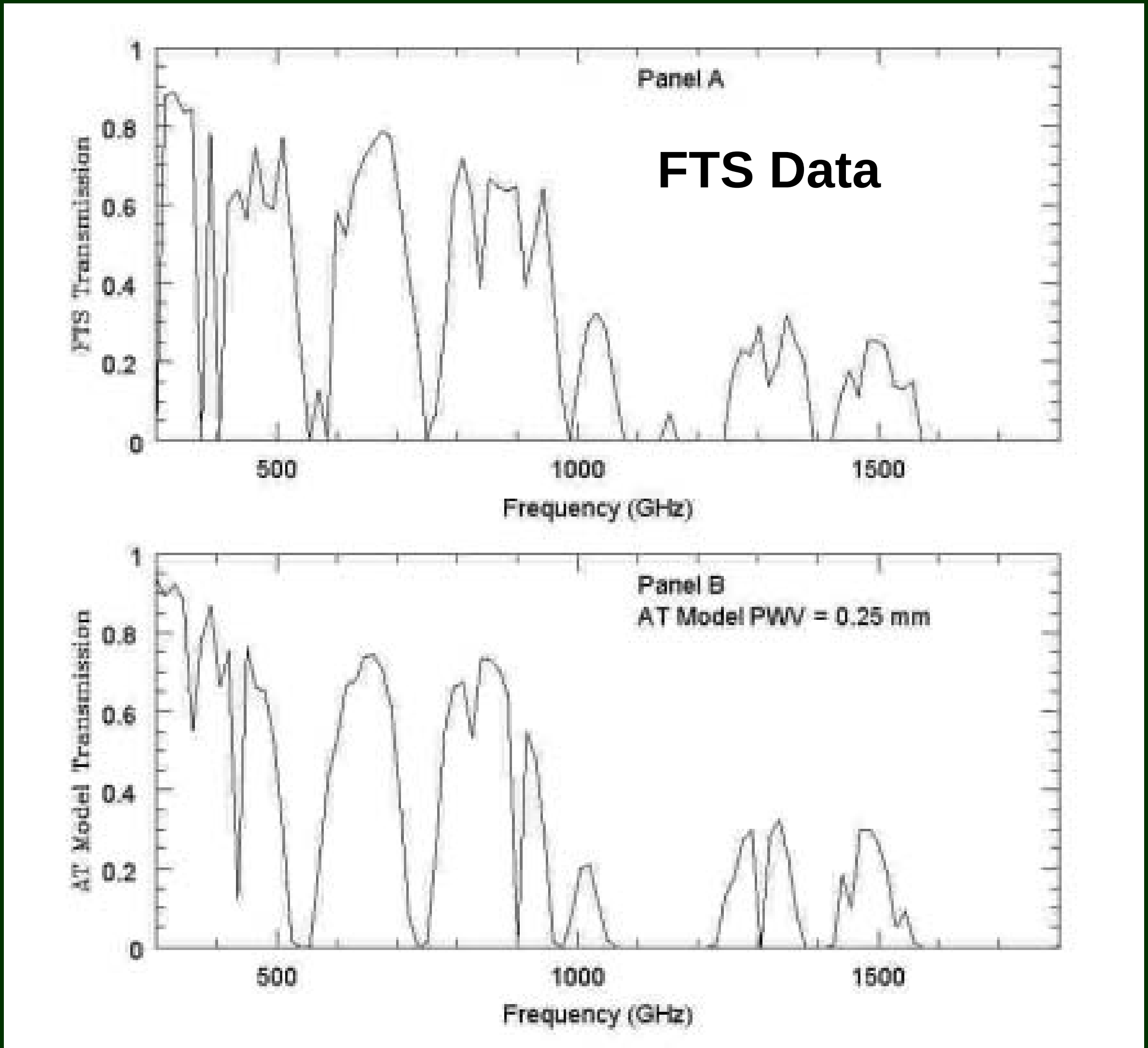
SPT 1000 Element Array



The South Pole Site

- Superb transmission measured at 200 um 25%
- PWV = 0.25 mm

Chamberlin et al. 2003



The Atacama 25 m Telescope Project

- Cornell and Caltech recently signed an agreement to participate in a study for developing a 25 m class submillimeter telescope.

- This facility is to be completed in about 2012.

- Since the AT 25 is a relatively late player in this field – it is critical that it cover sufficient new phase space to pursue compelling new science.

The Atacama 25 m Telescope Project

- Aperture: 25 meter class is significantly larger than APEX, SMT, CSO or JCMT – ensures that it is not confusion limited in exposures of 24 hours or less.

- Water Vapor Burden: Need consistently lower burden than 1 mm to reach the short submm windows

- Surface Accuracy: Desire high surface accuracy (~ 12 um rms) to obtain good efficiency in the 200 um window (1.5 THz)

- Field of View: Faint source surveys a forte – therefore requires large FOV > 5' which could be populated with 10,000 element arrays.

AT 25 m Instrumentation

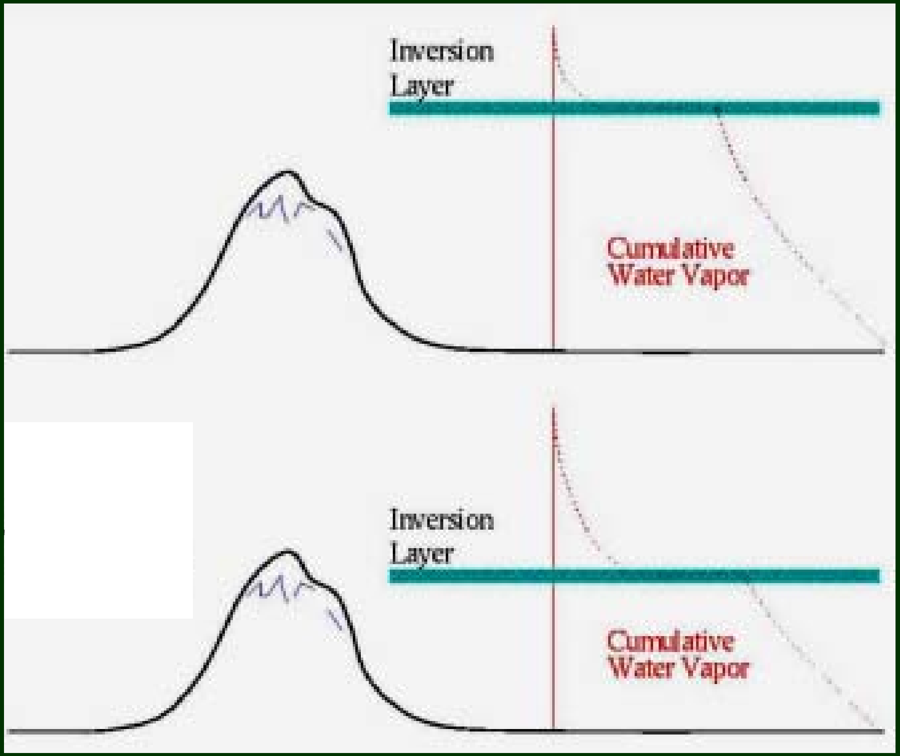
- Bolometer Array Cameras – more than 10,000 pixels
  - 350 and 450 μm at first light
  - 620 and 850 μm, likely in same dewar – filter wheel?
  - 200 μm likely 3rd band
- Direct Detection Spectrometers
  - R =1000, 4 x 256 short slit grating spectrometer
  - R = 100, Z-Spec like wave-mode coupled spectrometer
- Coherent spectrometers for high spectral resolution science: e.g. Galactic starformation studies

The Site: Peaks Near the Chajnantor Plain

Key Question:
Does the inversion layer descend below nearby peaks?

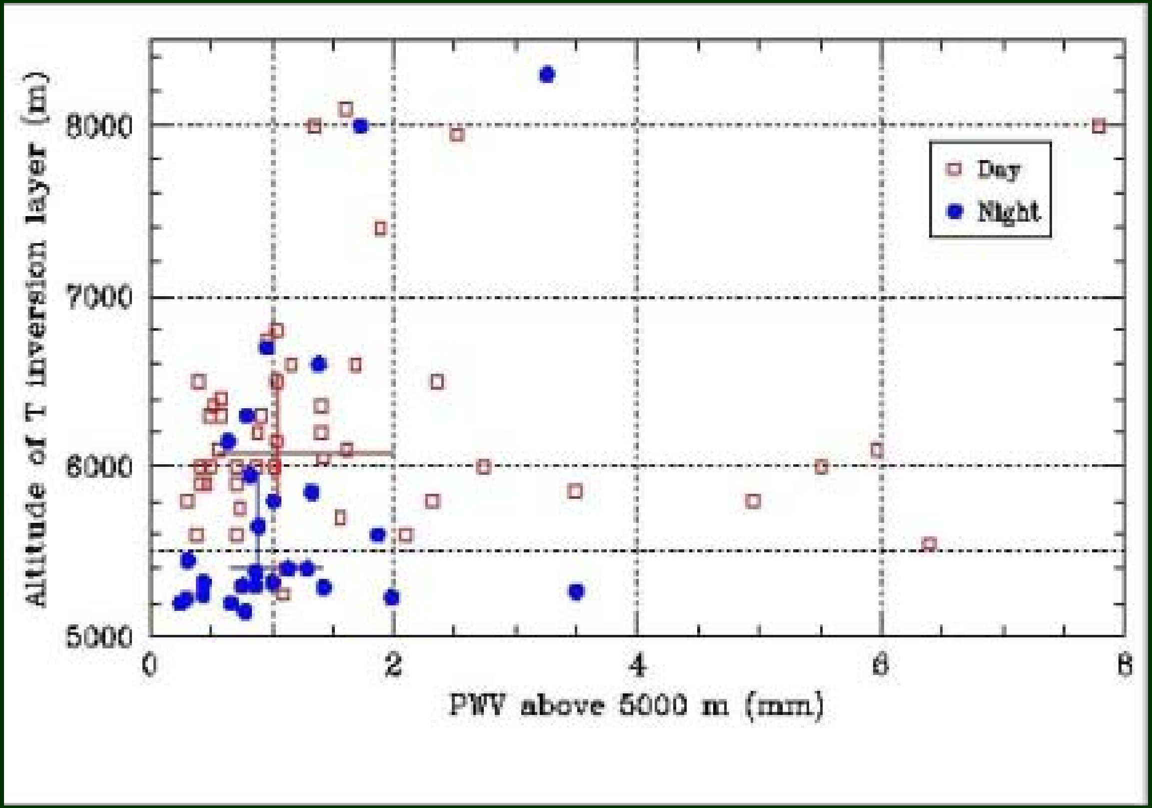
Case I:

Case II:



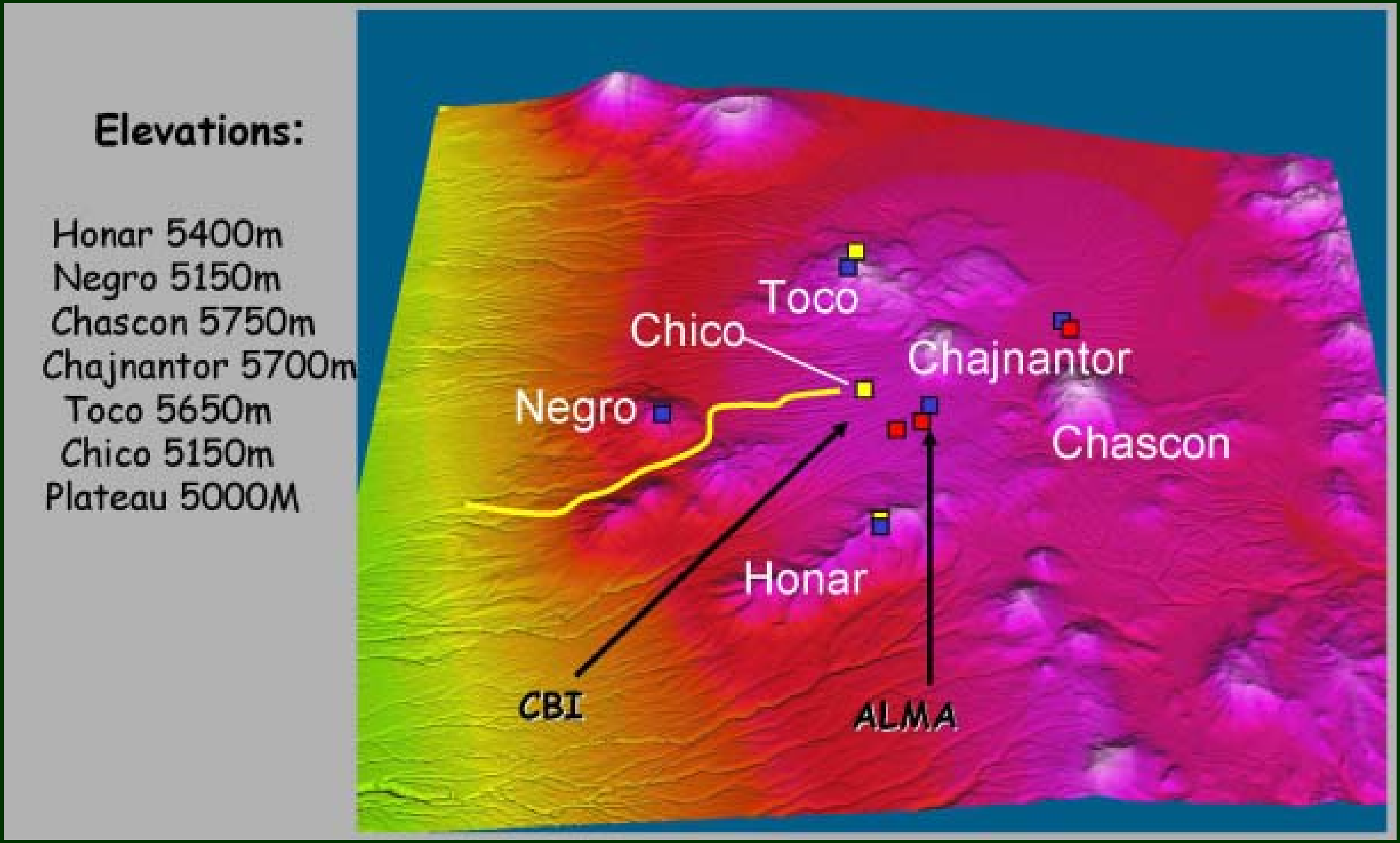
The Site: The Inversion Layer

The Key Answer: Yes, it appears that it does!



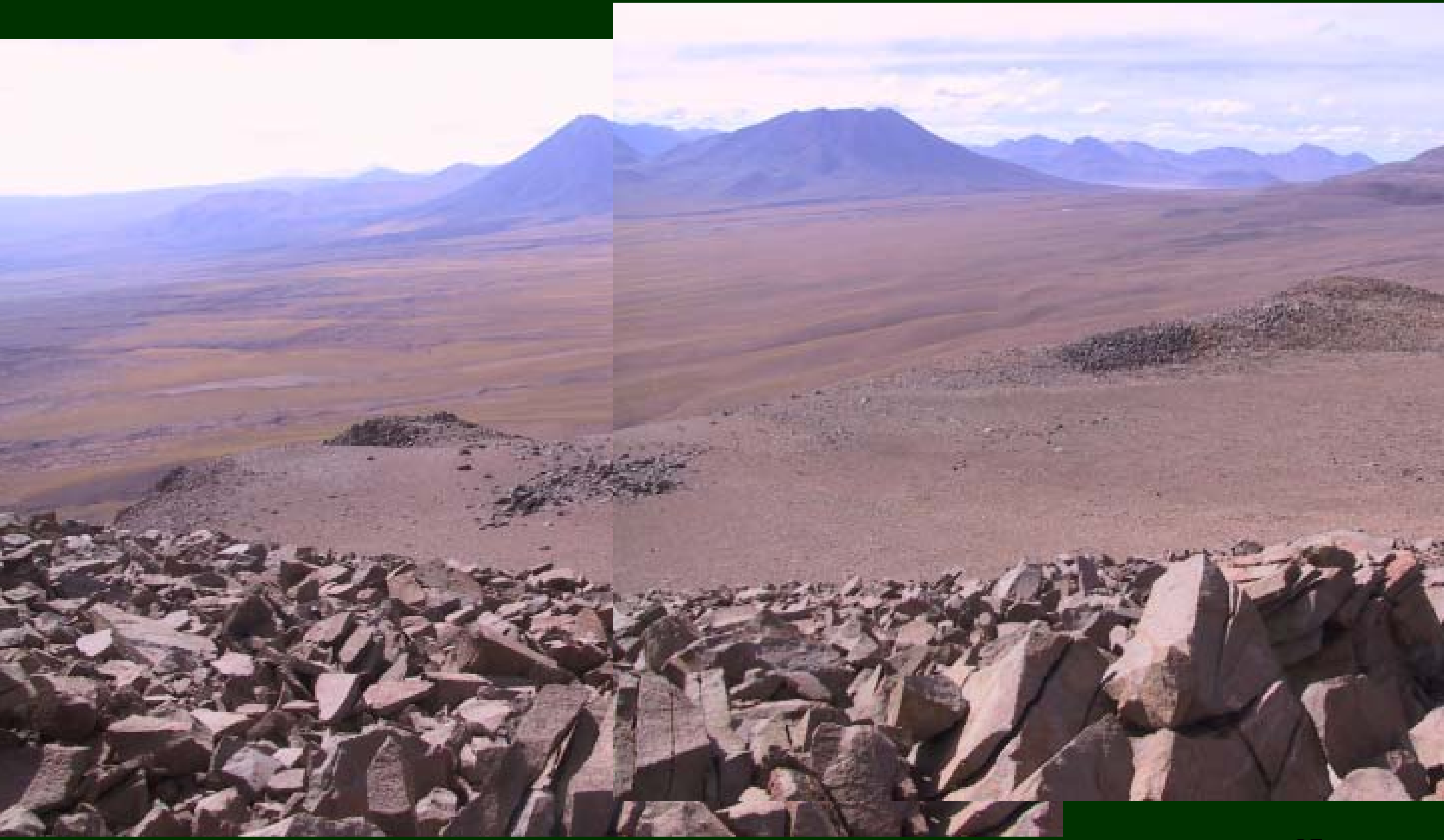
Ongoing site survey to verify the gains.

The Site: Which Peak?



- High sites include Chascon and Honar
- A more accessible site is Negro – may have equivalent water vapor burden

Cerro Negro from Honar

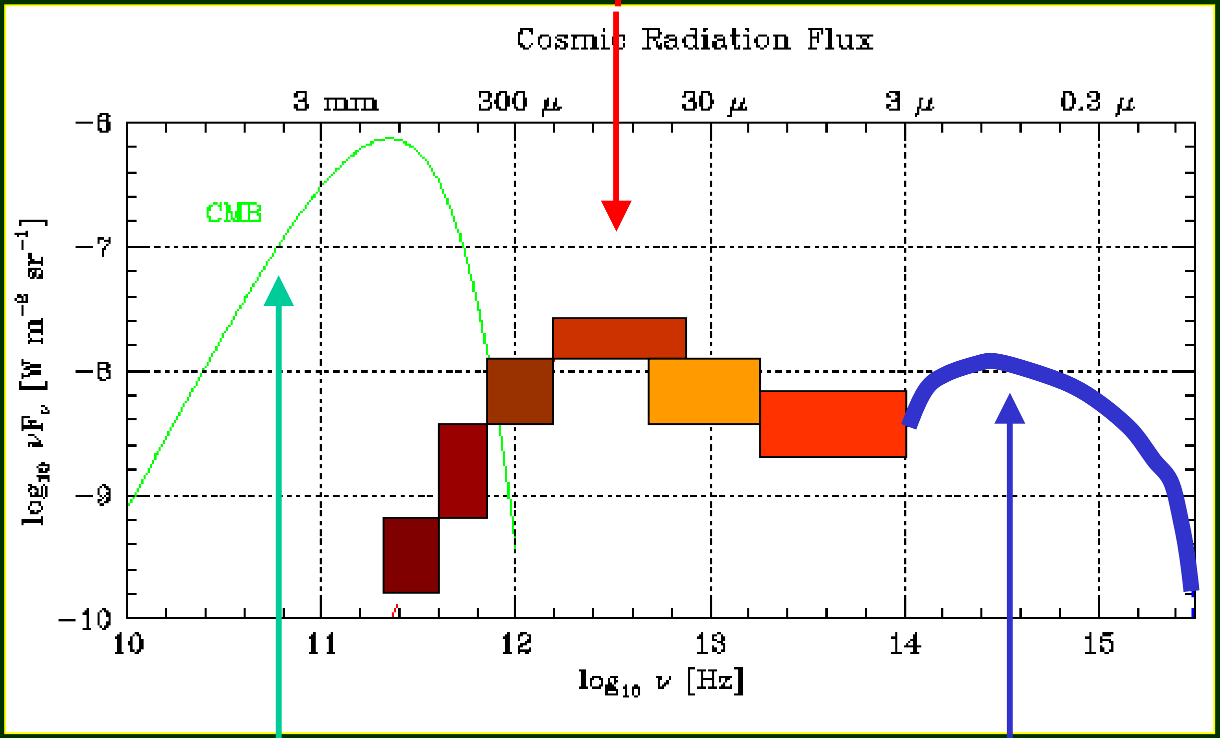


Science Goals

- Galaxy Formation and Evolution
- ISM, Disks, Star and Planet Forming Regions
- CMB and the SZE
- Solar System Studies
- Lets consider two particularly illustrative cases:
  - Galaxies in the Early Universe
  - KBOs and Irregular Satellites in the Solar System

The Submillimeter Background

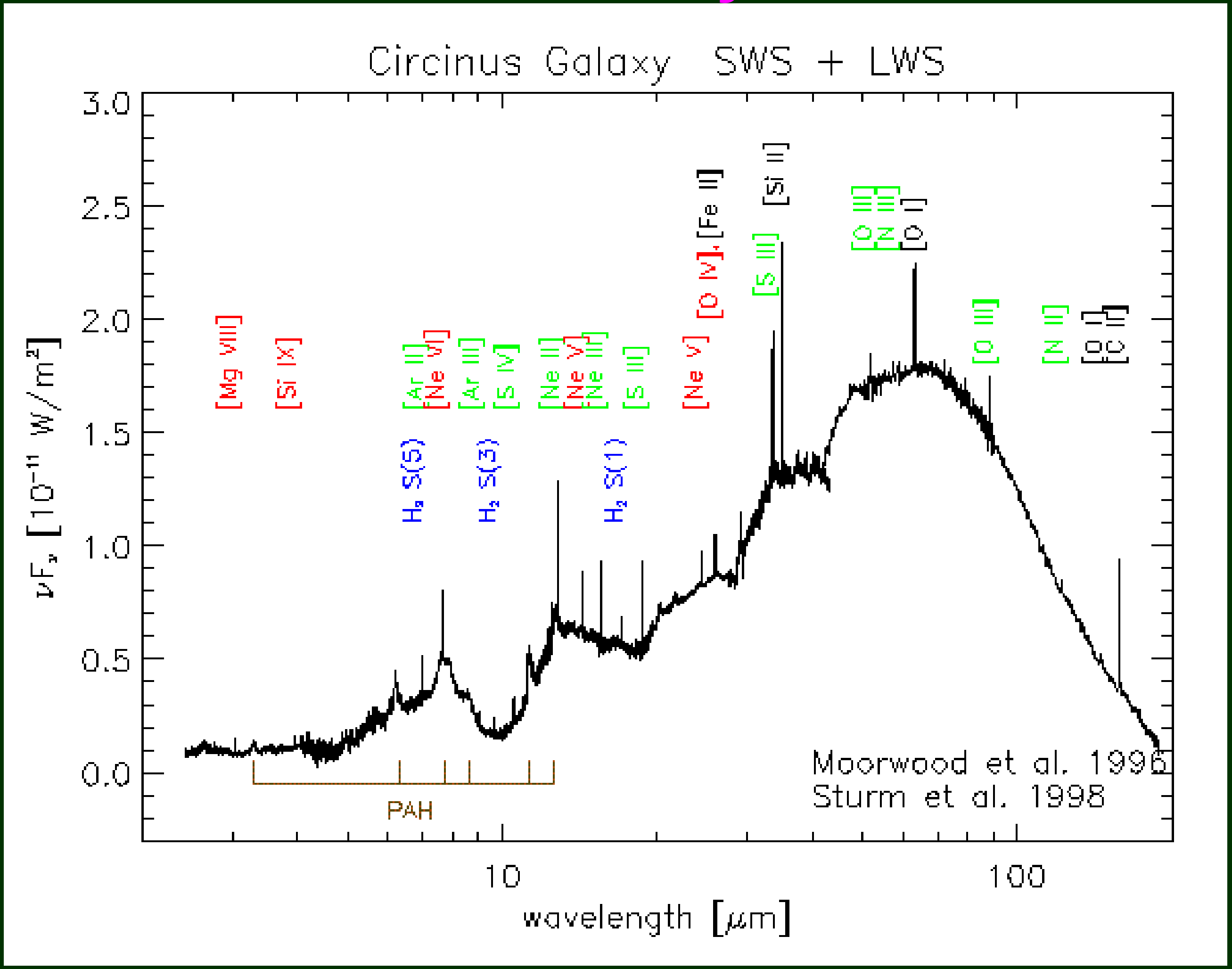
Photospheric light
Reprocessed by dust



Microwave Background

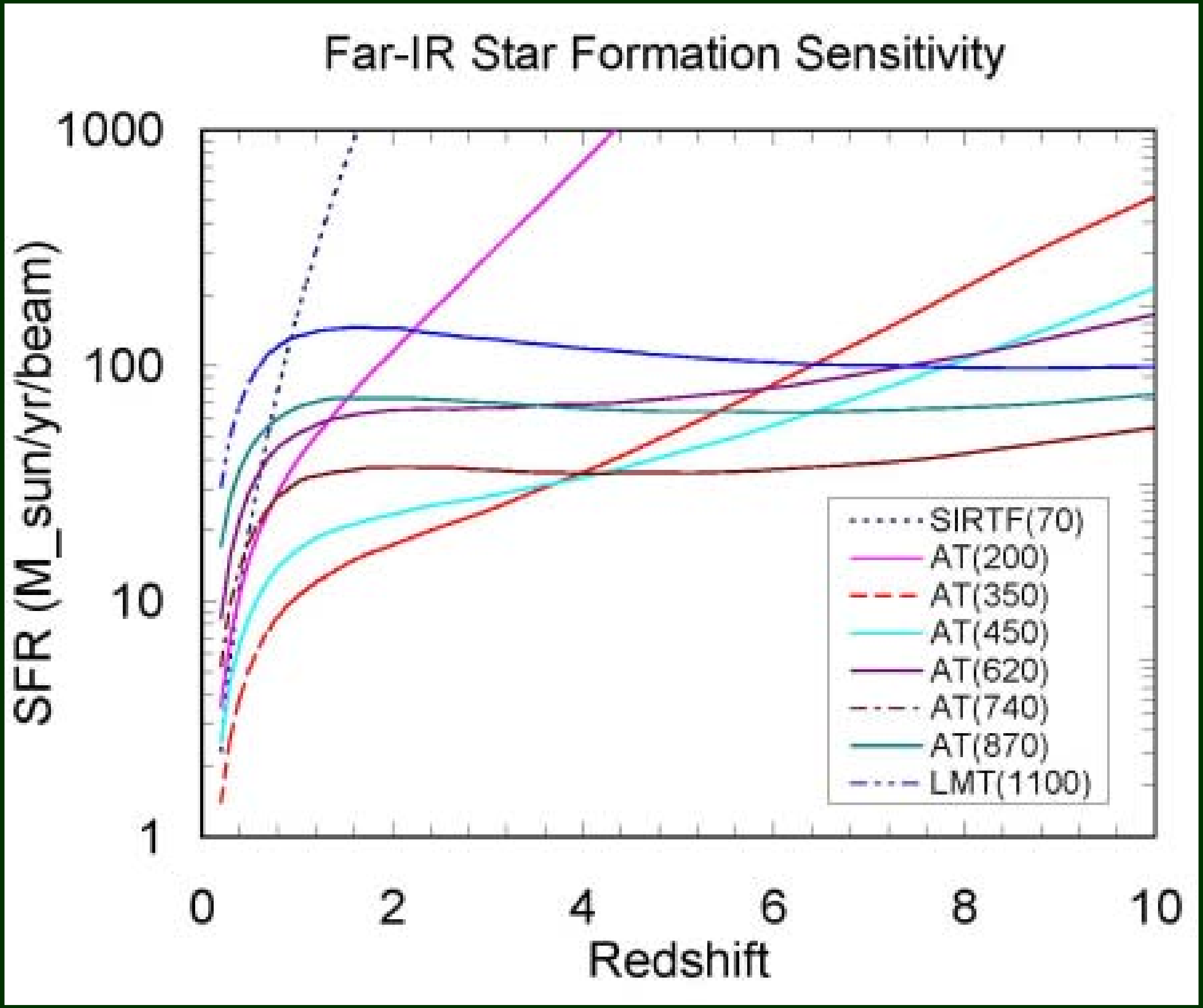
Photospheric light
from stars

Starburst Systems



Starburst systems emit the vast majority of their light in the far-IR

Star Formation Sensitivity



For starforming galaxies, the far-IR luminosity is proportional to the star formation rate.

The AT will detect SFR~10-30 $M_{\odot}$/yr for z < 3, and SFR~40 - 100 at z ~ 10!

AT 25 m 5 σ, 10,000 sec

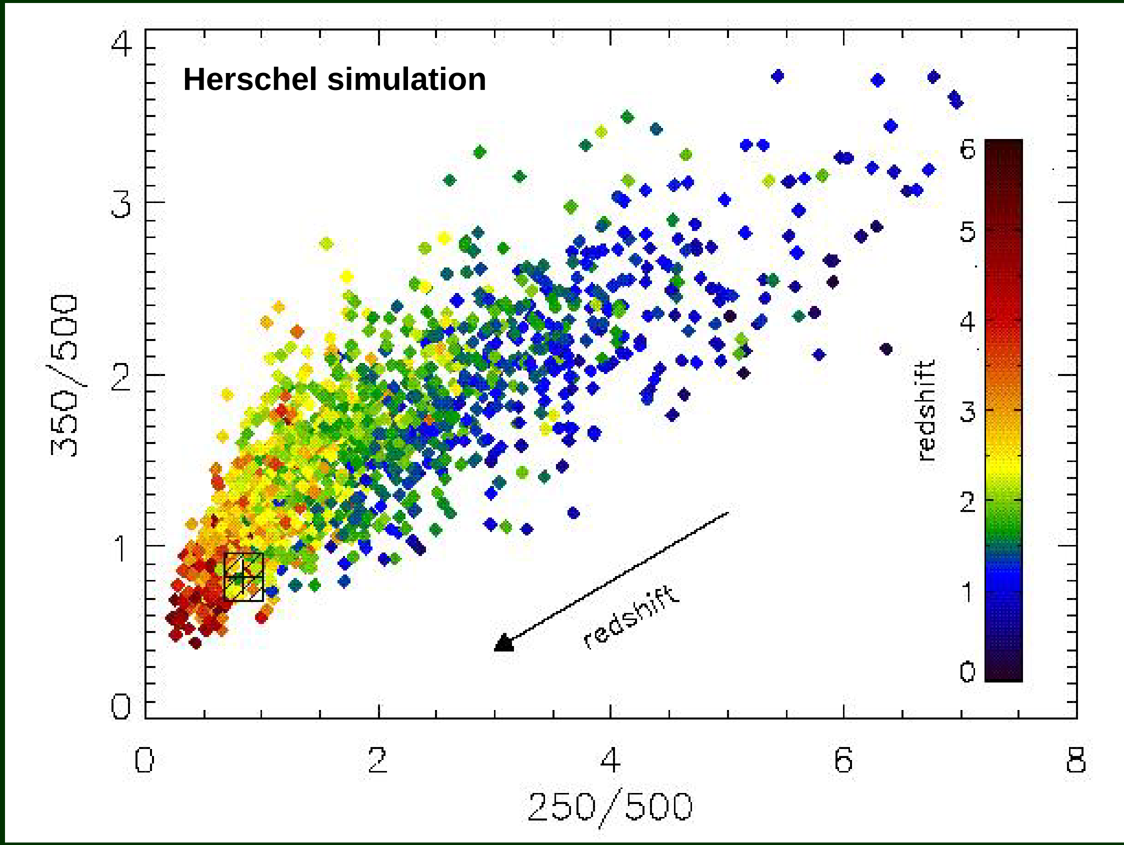
SIRTF, LMT(1100) confusion limited

Submm Photometric Redshifts

A 3000 hr survey with the AT might detect ~ 500,000 galaxies, mostly with z ~ 2 - 4, but easily up to z ~ 10 (if they exist)

Access to multiple FIR bands can yield photometric redshifts accurate enough (~ 20%) to allow investigation:

- Starformation history of the Universe
- Evolution of large scale structure



Redshifted far-IR Lines

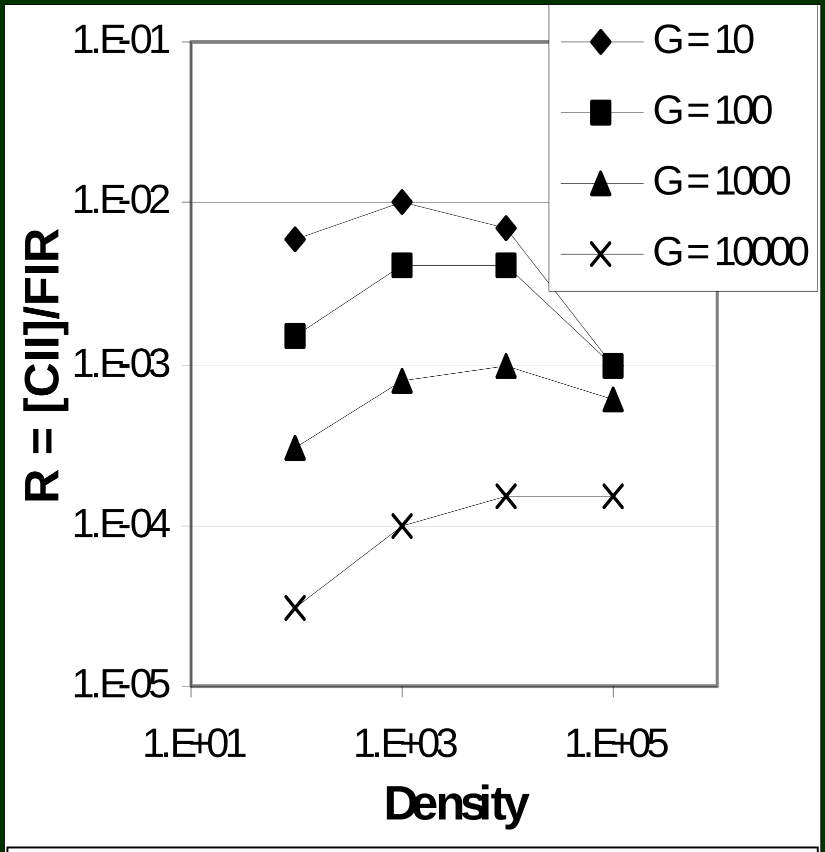
- Many of the galaxies detected in the continuum will be detectable also in spectral lines such as [OI] 63 um, [OIII] 88 um, [NII] 122 & 205 um and, especially, [CII] 158 um
  - [CII] 158 um emission from $5 \times 10^{10}\ L_{\odot}$ galaxy traceable between z=0.25 and z=4.8, as it gets redshifted across the submm telluric windows
  - [OIII] 88 um line emission from $2 \times 10^{11}\ L_{\odot}$ galaxy traceable at z ~ 1.3, 3 and 4.1
  - [OI] 63 um line emission from $7 \times 10^{11}\ L_{\odot}$ galaxy traceable at z ~ 2.2, 4.6 and 6.1
- FIR spectroscopy will allow the study of:
  - Gas cooling
  - The physical conditions in the star forming gas
  - The properties of the interstellar radiation field
  - The internal dynamics of primeval galaxies and of their merger histories.

Redshifted [CII]

- The [CII]/far-IR continuum is a sensitive indicator of the strength of the ambient ISRF
  $\Rightarrow$ Detection yields concentration of the starburst
  - High density systems cooling can come out in [OI] 63 um line
  - Line ratio yields PDR parameters
- ULIGS often have weak [CII] suggesting an AGN contribution to the far-IR

The physics is in the line to continuum ratio!

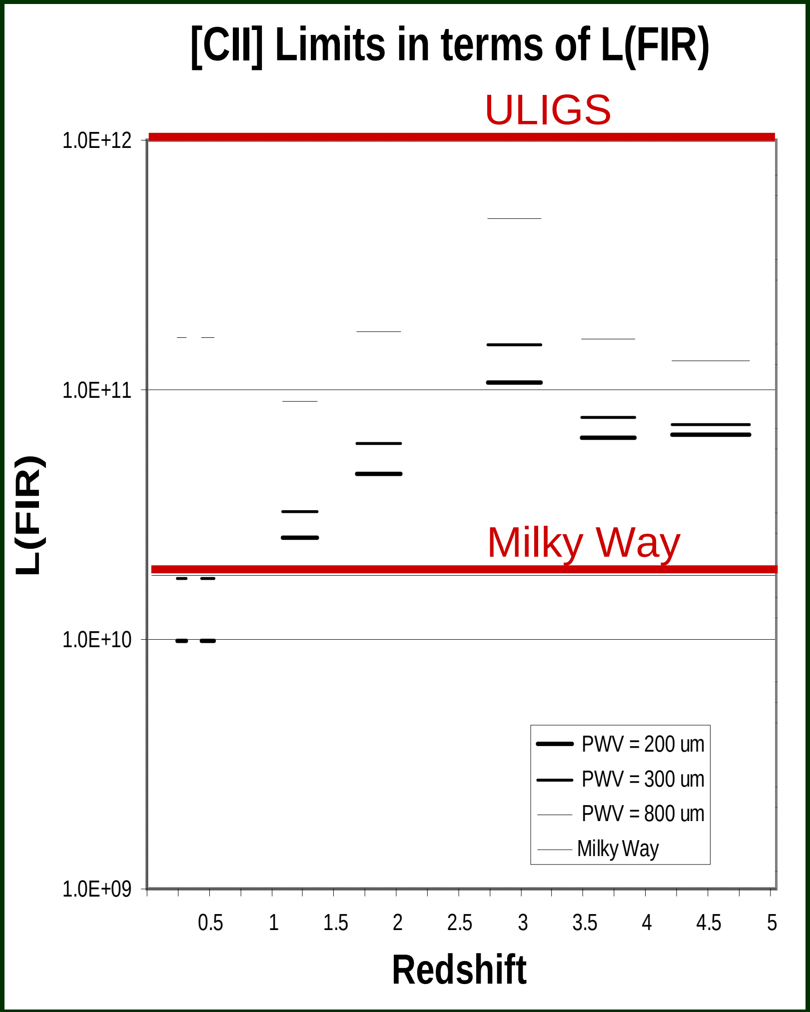
- Detecting [CII] from highly redshifted galaxies probes star formation in the epoch of galaxy formation



The [CII]/far-IR continuum ratio as a function of G (from Kaufmann et al)

Redshifted [CII] Emission Yields Far-UV Field Strength and Redshifts

- *The [CII] line is detectable at $z > 5$ for $L_{far\text{-}IR} > 5 \times 10^{10}\ L_{\odot} \sim 2\ L_{Milky\ Way}$!*
- *For ULIGS with [CII]/far-IR > 1.5 x 10^{-4} [CII] is easily detected at z > 5!*
- *However, it is the lower luminosity systems that are most interesting with respect to galaxy assembly – these will likely have relatively bright [CII] line emission*
- *[CII] line is uniquely bright, but redshifts can be verified (again with a gain to the physical understanding) by observing the [OI], [OIII] or [NII] lines*



AT 25 m Primeval Galaxy Survey

- The AT brings a unique combination of properties:
  - statistical wealth (number of detections)
  - access to multiple submm bands (photometric z)
  - quality of SED determination
  - redshift and star formation rate stretch
  - access to fine structure FIR lines
  - ability to carry out deep surveys

These ensure that the AT 25 m telescope will be a prime instrument for study of galaxy formation

Confusion in the Submm

Studies of faint Solar System obsjects illustrate well a most important concern for FIR/submm telescopes:

CONFUSION

Kuiper Belt Objects

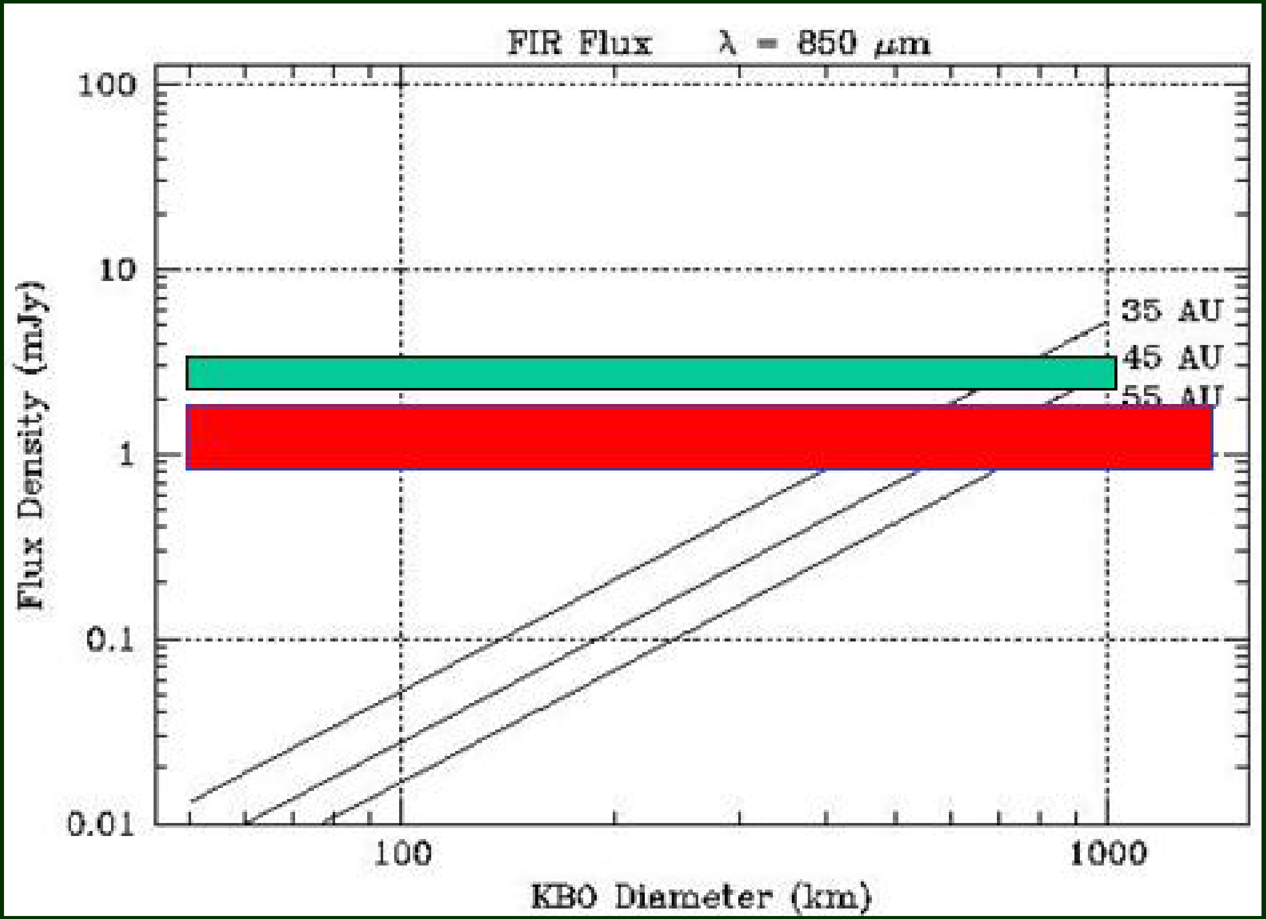
- Trans-Neptunian objects at ~ 40 to 50 AU
- Formed early in the outer reaches of the solar protoplanetary disk
- Several hundred known
  - Pluto (D~2400km)
  - Charon (D~1200 km)
  - Varuna (D~900km)
  - Chaor

- Optical/NIR observations yield orbital parameters – flux, not size
- KBOs have equilibrium temperatures ~ 45 K $\Rightarrow$ far-IR emitters
- Pluto, Charon, Varuna & Chaor have been detected at 850 mm by JCMT, *yielding sizes, albedos and surface properties.*

KBOs and Confusion: SCUBA

SCUBA

5-sigma
10,000 secs
PWV = 1.5 mm



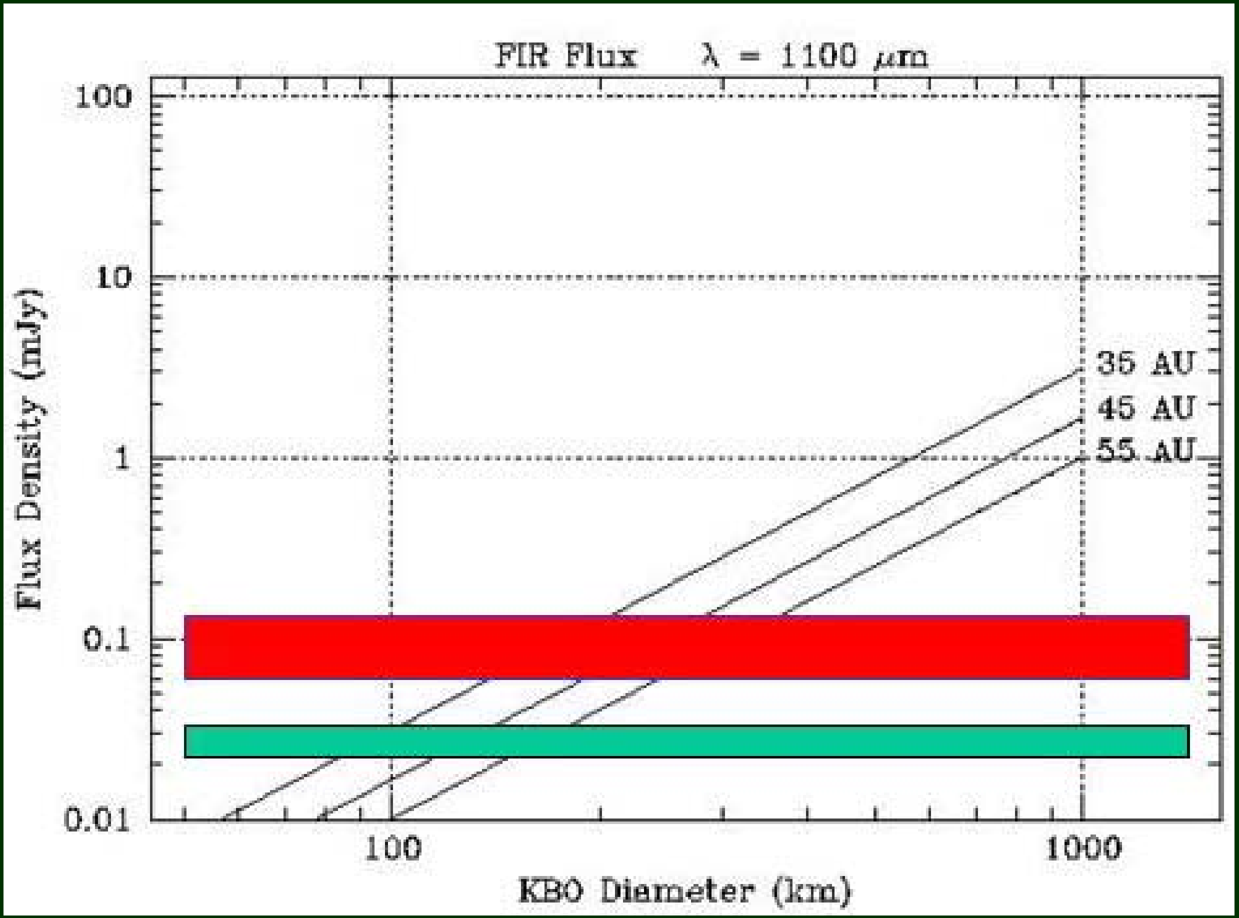
JCMT confusion limit

- SCUBA confusion limit is about a diameter of 500 km
- Not many KBOs that large!

KBOs and Confusion: LBT

LMT

5-sigma
10,000 secs
PWV = 1.5 mm



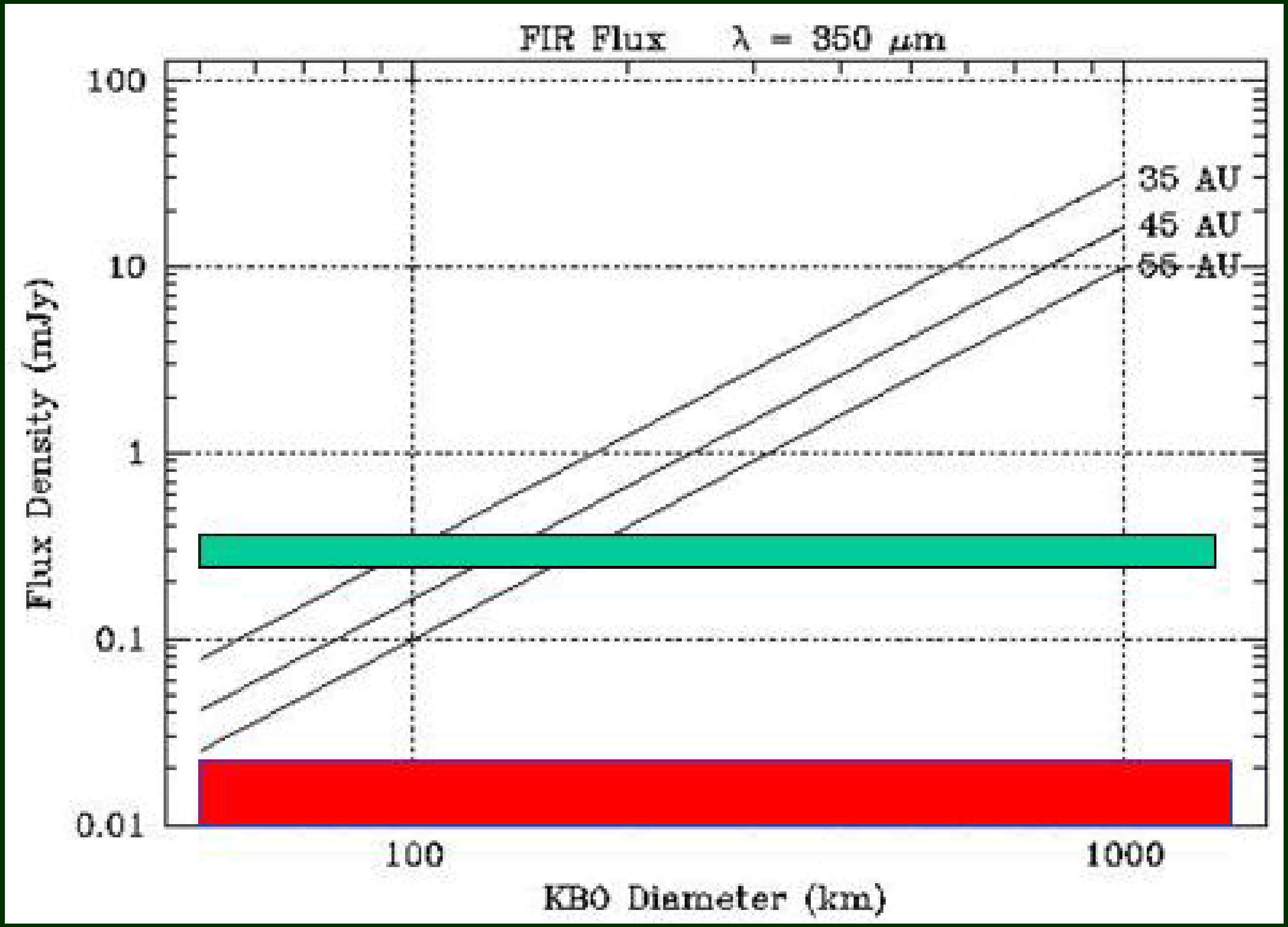
LMT confusion limit

- Due to its much larger aperture, the LBT does better – but its confusion limit corresponds to ~ 200 km KBOs

KBOs and Confusion: AT 25 m

AT 25 m

5-sigma
10,000 secs
PWV = 1.5 mm



AT 25 m confusion limit

- The AT easily detects KBOs with D~120 km in few hours
- Confusion level much lower –

With sufficient integration, can go to 30 km or so!

Irregular Satellites: AT 25 m

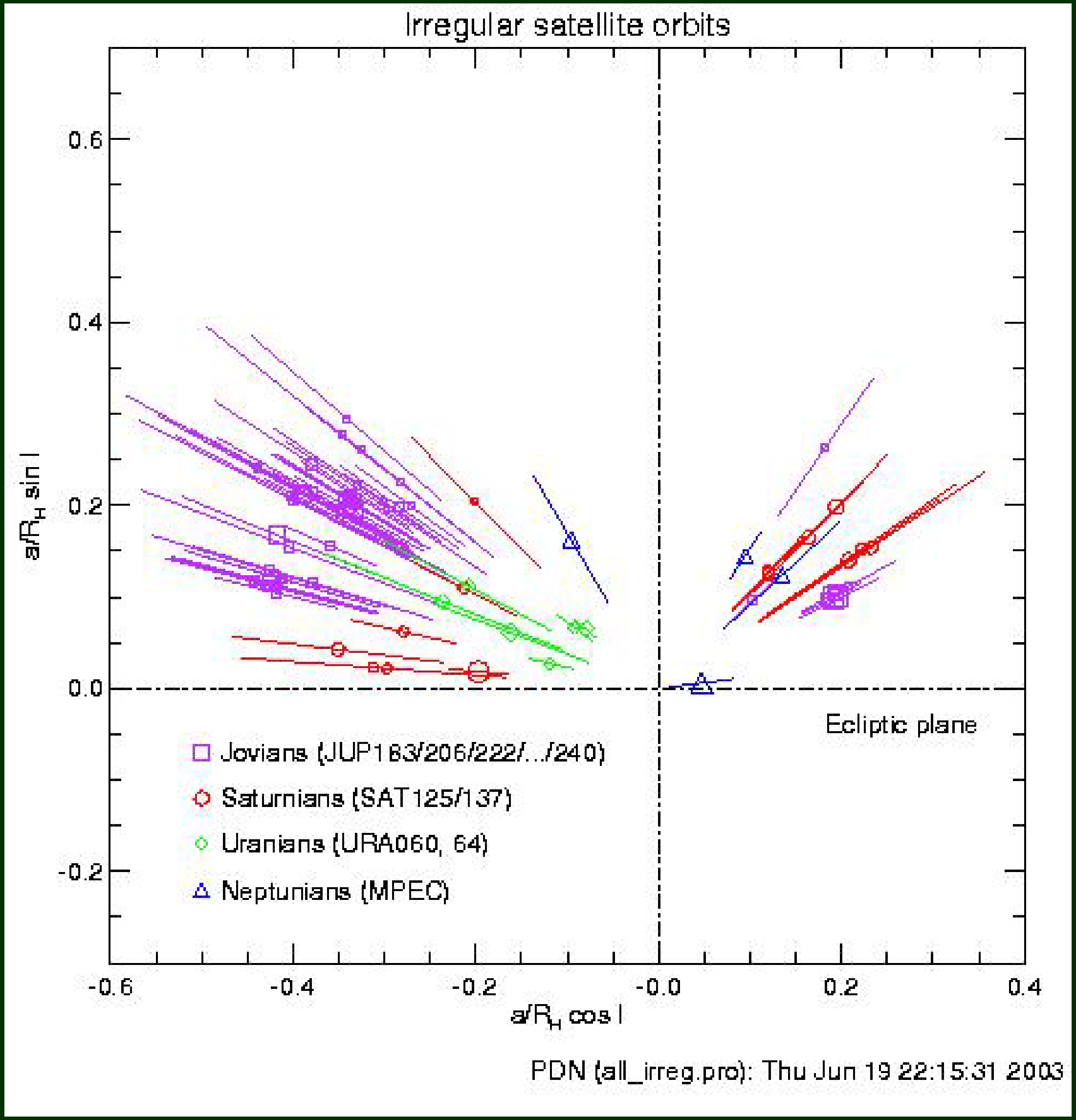
- **Hundreds of thousands KBOs with D > 30 km may exist**

- **The AT could reveal the size function and surface properties of the KBO population.**

- **During the deep searches for primeval galaxies, KBO science could run in a serendipity mode:**

may be able to detect ~ 1 KBO per frame.

Why do we care?



KBOs come in families – are families the result of fragmentation of larger bodies (parents)?

- **Thermal emission yields sizes**
- **Optical emission and sizes yield albedos**

If albedos are the same, then fragments come from a single parent

Sensitivity Comparisons

- Surprisingly enough, in the continuum, the AT 25 m is competitive with ALMA in raw point source sensitivity. At 350 um with $PWV_{AT\ 25}$ = 0.5 mm, PWV_{ALMA} = 0.8 mm:

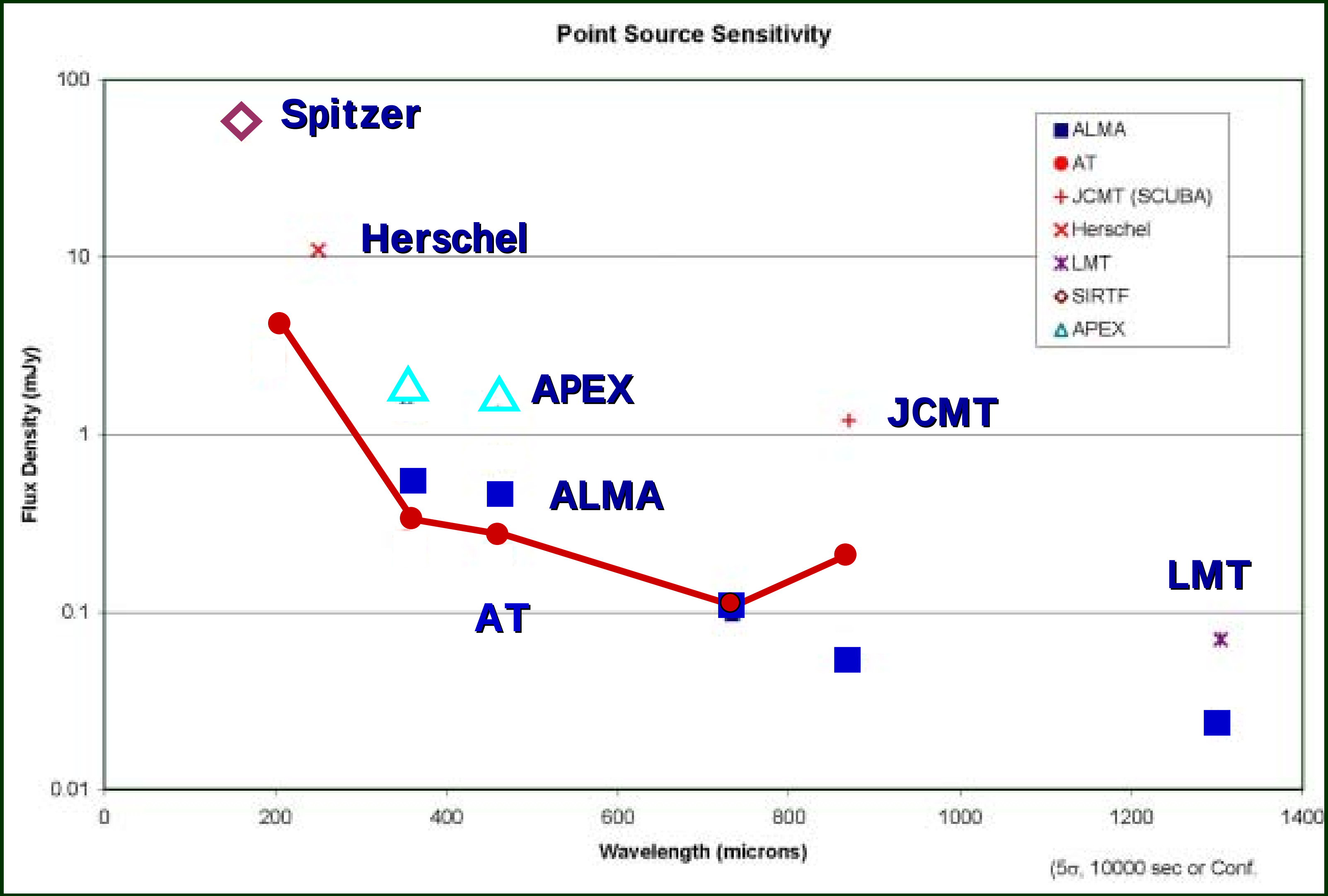
$$\Delta F \propto ((T_{rec}+T_{bk}) \cdot \sqrt{BW}) \div ((\eta_{sky} \cdot \eta_{tel}) \cdot A_{tel} \cdot n_{tel})$$

	η_{sky}	η_{tel}	$T_{rec}+T_{bk}$	BW	A_{tel}	n_{tel}
AT 25	0.53	0.83	150	100	490	1
ALMA	0.35	0.60	400	8	113	64

$$\Delta F_{AT\ 25}/\Delta F_{ALMA} \sim 3/4$$

- The large format arrays with single dish observatories ensure the mapping speed is much higher
- Of course, no single disk will approach the angular resolution of ALMA
- AT 25 m finds the interesting sources for which ALMA can obtain vital spatial information

Sensitivity Comparisons



Conclusions

- Several powerful new facilities coming on line or planned
- These facilities are planned for the best sites to take advantage of the short submillimeter windows
- Development of large format bolometer arrays key to success
- Sites, apertures, and bolometer arrays enable these facilities as “finders” for the ALMA array